BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D. C. 20036

SUBJECT: A LM Rescue Strategy Requiring No On-Board Targeting Case 310

DATE: March 28, 1968

FROM: S. L. Levie, Jr.

ABSTRACT

A four-burn strategy for LM rescue is proposed in which provisions are made for all necessary real-time targeting to be done on the earth. Rescue rendezvous is constrained to occur in the dark and hard docking in the light. The strategy has been applied to rescuing the LM from a 10 nm by 40 nm ascent ellipse.

In this application the total rescue delta velocity is well within the present budget of 791 fps, and the braking delta velocity can be kept below about 140 fps. The elapsed time between the strategy's first and last burns is less than four hours. Perilunes on all CSM orbits are above 50,000 ft. It is anticipated that these figures will hold for more general applications of the strategy.

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MEMORANDUM FOR FILE

1.0 INTRODUCTION

This memorandum presents a simple, effective strategy for CSM rescue of the LM. Developed as part of an effort to reduce substantially the computational requirements on the CSM and LM guidance computers, the strategy requires no on-board targeting capability for either vehicle. Time for earth tracking and earth targeting is provided for those maneuvers which must be targeted in real-time. The remaining maneuvers can either be targeted prior to a mission or uplinked to the CSM before it goes out of sight behind the moon.

The strategy's rationale will be illustrated by developing the case of rescuing the LM from a 10 nm by 40 nm Hohmann ascent trajectory[1]. Fuel-wise, this is one of the more difficult rescues the CSM might be called upon to make. The strategy has been applied only to this case; however, preliminary investigations indicate that it is applicable to other phases of LM ascent as well as to the LM's Hohmann descent trajectory. It is expected that the delta velocity requirements for such applications will not significantly exceed those developed in the 10 nm by 40 nm ascent trajectory application.

The targeting computations for rescue, assumed for this study to be done on the earth, can be done on-board with the programs currently planned for the Apollo Guidance Computer.

2.0 RESCUE STRATEGY

The rescue strategy utilizes four CSM burns. The first two constitute a Hohmann transfer to a circular phasing orbit. The altitude of this orbit depends on the expected range of CSM lead angles at initiation of the rescue. The CSM

[1] These figures are consistent with those used in Reference 1, which examines LM ascent with simplified guidance and targeting logic.

coasts in its circular phasing orbit through approximately 360°. The third burn--the TPI[2] burn--occurs when the CSM is near the center of the lunar disc, as viewed from earth. The TPI burn is adjusted so that the fourth burn, or braking maneuver at rendezvous, occurs in the dark and requires a minimum velocity change.

It will be shown that the burns of the Hohmann transfer may be precomputed on the earth. Because TPI occurs near the center of the lunar disc, good earth tracking and earth targeting are made possible for both the third and the fourth burns of the rescue sequence.

2.1 Hohmann Transfer

It will be assumed that when the LM reaches apolune on its 10 nm by 40 nm ascent ellipse and at that point attempts a circularization burn, it is found to be without propulsive ability. For mathematical convenience, it is assumed that the CSM, which is in a 60 nm circular orbit and leading the LM by some angle θ, performs its rescue sequence initiation (RSI) maneuver at this instant. In reality there would be a time delay before the maneuver could be initiated, but the effect of reasonable delays on the phasing and on the delta velocity requirements is negligible. The RSI lead angle, θ, depends on when in its launch window the LM leaves the lunar surface.

In the rescue sequence proposed here, the RSI maneuver is the first burn of a Hohmann transfer of the CSM to a circular phasing orbit of altitude H. It will be shown that, given the landing site longitude and the expected range of θ resulting from the allowable launch window, that a value of H can be selected such that the delta velocity of the fourth burn is a minimum over the expected range of θ. This makes possible the computation of the parameters for the Hohmann transfer well in advance of a mission. Thus real-time computations are not required for the Hohmann transfer maneuvers.

For certain landing sites, additional refinements to the strategy for targeting the Hohmann burns are available. For eastern sites, sufficient tracking opportunity exists for

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[2]Terminal phase initiation.

reoptimizing the phasing orbit altitude for the actual value of θ resulting from LM launch. For western landing sites, sufficient tracking is available prior to the second Hohmann burn to allow computation of an update for the maneuver's parameters. This study does not take advantage of these possible refinements.

2.2 Terminal Phase

After the CSM has travelled through 360 + F degrees (a criterion for choosing F will be presented shortly) in its phasing orbit, it is to execute a maneuver computed to place it on a LM-intercept trajectory. This is the terminal phase initiation (TPI) maneuver. To be able to compute this maneuver and any subsequent midcourse correction with confidence, good earth tracking of the CSM before and immediately after TPI is required. This can be achieved by having TPI occur near the center of the lunar disc, as viewed from the earth. Accordingly, the TPI maneuver is located at zero degrees selenographic longitude.

With the TPI location defined, F can be computed, given the following: L, the landing site longitude; θ, the CSM lead angle at RSI; and A, the central angle for LM ascent to perilune on the 10 nm by 40 nm ellipse (A will be approximately 10°). Referring to Figure 1, if at RSI the CSM leads the LM by θ, then the CSM's transfer orbit perilune will be θ degrees west of the LM's perilune, and therefore θ+A degrees west of the landing site. Since the site is at longitude L, the CSM must therefore fly through F = L - (θ+A) degrees from transfer orbit perilune to zero degrees longitude[3].

If the phasing orbit altitude, H, is specified, the time from RSI to TPI can readily be computed as

$$\Delta t = \pi \sqrt{\frac{\left(R_M + \frac{60+H}{2}\right)^3}{\mu}} + 2\pi\left(\frac{360+F}{360}\right)\sqrt{\frac{\left(R_M+H\right)^3}{\mu}} \quad ,$$

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[3]The assumption that the trajectories lie in the moon's equatorial plane has been made here. Although this condition will in practice never occur, it is a good approximation for Apollo flights and for presenting this strategy.

in which R_M is the lunar radius and μ is the lunar gravitational constant. (A criterion for choosing H will be stated shortly.) Knowledge of Δt is necessary for the computation of the LM's position at TPI.

2.3 Rescue Rendezvous

The final maneuver of the terminal phase (TPF) occurs when the CSM has flown from TPI through a central angle δ. The choice of δ will depend primarily on rendezvous requirements[4]. The principal requirement is that the maneuver should occur in the dark, at least sixty degrees before the LM would arrive in the sunlight. This allows rendezvous maneuvering to occur in darkness, followed by hard docking in sunlight.

Figures 2 and 3 depict the geometry involved in determining the value of δ for an assumed landing site on the equator at 40° East. Figure 2 shows that ϵ, the sun elevation at LM landing, is equal to the difference in longitude between the landing site and the dawn terminator. Current planning calls for the sun elevation at LM landing to be between 5° and 15°. Figure 2 assumes a 10° sun elevation. Figure 3 shows the landing site at LM launch, about 24 hours--or 13° of lunar rotation--after LM landing. The figure also shows the required location of TPF[5]. Since L = 40°, one sees from the figure that δ must be 103°.

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[4] Ideally, one would like to adjust δ such that the LM would be very near apolune at rendezvous, since its speed is smallest there. However, since all the lunar orbits in the Apollo program are nearly circular, any beneficial effects of rendezvousing near apolune will be slight. Therefore the location of the LM at rendezvous is of small importance, and the effect of δ on rescue delta velocity costs is small.

[5] The TPF location shown in Figure 3 does not include compensation for the moon's rotation during the interval from TPI to TPF. This rotation, which amounts to about 0.5°, may be ignored in selecting δ.

A similar calculation for a site at L = -40° indicates δ = 185°. This would place the LM very near apolune at rendezvous. However, to avoid possible computational difficulties when applying the strategy and using conic routines, an arbitrary upper limit of δ = 160° has been established. According to Footnote 4, this is certainly adequately close to 185°.

For sites west of -15° longitude, the required δ would always be greater than 160°. Therefore, for these sites a value of 160° will be used in lieu of the computed δ, to insure that no convergence problems will be encountered. For the sites east of -15° longitude, the computed value of δ will be used.

2.4 Phasing Orbit Altitude

In the general case, the CSM's phasing orbit altitude, H, as yet unspecified, can be used to adjust the phasing at TPI such that the terminal phase of the rescue uses as little CSM propellant as possible. In particular, H can be used as a parameter for minimizing the TPF fuel requirement. The best value for H will depend on the value which is selected for δ, and on the RSI lead angle, θ. As has been indicated, δ is a constant for a particular landing site. However, θ depends on the CSM's lead angle at LM injection, and this cannot be known prior to a mission. Nevertheless, it is possible to specify beforehand a value of H for which the TPF fuel costs will be small for all lead angles resulting from the expected LM launch window (this is shown in Section 3.0)[6]. Furthermore, for eastern landing sites there will be time after LM injection for earth tracking and real-time computation of the optimum H.

2.5 Time Estimate

For the range of δ indicated above, the total time interval from TPI to TPF is about half of a LM period. Since the interval from RSI to TPI is about one and a half periods, the total duration of the rescue sequence is about two LM periods, or four hours. Noting that after rescue rendezvous about two hours might be required for coasting into sunlight, docking, and transferring of the crew, and also that RSI occurs

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[6] But the TPF fuel cost will be a true minimum for only one value of the lead angle.

approximately one hour after LM launch, then about seven hours transpire between LM launch and crew transfer. This estimate lies within the LM ascent stage lifetime of nine or more hours.

3.0 NUMERICAL SOLUTION

The mathematics of the rescue strategy described above have been applied to the particular problem of initiating LM rescue when the LM arrives at apolune on its 10 nm by 40 nm elliptical trajectory. The CSM lead angle, θ, at this point will lie somewhere in the interval 12.9° to 17.3° for a landing site at 40° East, and in the interval 11.7° to 15.6° for a landing site at 40° West[7]. Computations were made for both of these sites.

For the eastern site, δ was taken as 103°, as computed earlier. H was chosen such that the minimum of the TPF delta velocity corresponded to θ = 15.1°, the center of the expected interval. This value is H = 36.05 nm. In Figure 4 are plotted, as functions of θ, the total rescue delta velocity, the TPF delta velocity, and another important quantity: the terminal phase orbit's perilune altitude. (This figure should be kept above 50,000 ft, for CSM safety in case of difficulty.) It is to be observed that for all values of θ in the interval 12.9° to 17.3°:

1. Rescue delta velocity is below 380 fps.
2. TPF delta velocity is below 138 fps.
3. Terminal phase perilune is above 9.5 nm.

For the western site, δ was taken as 160°, as suggested earlier. H was chosen to place the minimum of the TPF fuel requirement at θ = 13.7, the center of the expected interval. This is accomplished with H = 37.52 nm. Figure 5 plots as functions of θ the rescue delta velocity, the TPF delta velocity, and the terminal phase orbit's perilune altitude. For all values of θ in the interval 11.7° to 15.6° it is found that:

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[7] Reference 1 gives the range of CSM lead angles at LM injection for these sites. Knowing that the CSM loses 9.2° of lead as the LM travels from perilune to apolune allows the computation of the intervals used here.

1. Rescue delta velocity is below 275 fps.

2. TPF delta velocity is below 75 fps.

3. Terminal phase perilune is above 13 nm.

For practical purposes, the most important aspect of the results above is that for a given lunar landing site near the equator, δ and H can be preselected to give acceptable values of important quantities, for all expected lead angles. It is to be noted that if H can be selected in real-time, then it is possible to make the minimum TPF delta velocity correspond to the actual value of θ.

4.0 SUMMARY AND CONCLUSIONS

A simple strategy for LM rescue has been presented. The rationale of the strategy has been illustrated by applying it (with favorable results) to the difficult case of rescuing the LM from a 10 nm by 40 nm elliptical ascent trajectory.

The strategy uses four CSM burns. The first two place the CSM in a circular phasing orbit. The third, which occurs near the center of the lunar disc, places the CSM on a LM-intercept trajectory chosen such that the terminal, or braking, burn requires a minimum of delta velocity.

The strategy was designed with the intent of keeping real-time rescue computations simple and allowing full use of the RTCC. This last aim is achieved by providing good earth tracking of the CSM before and after the TPI burn. Contributing to the simplicity of the strategy is the fact that the constants affecting the first two burns may be computed prior to launching the mission.

The strategy offers rescue delta velocity costs (including braking phase) of less than about 400 fps. Even after allowing an additional 200 fps for a Hohmann transfer to a 60 nm orbit, from which transearth injection might be made, the delta velocity cost is well within the budget of 791 fps. The strategy requires a braking delta velocity of less than 140 fps, and it allows safe perilunes throughout the rescue. The rescue requires four hours at most.

Although the strategy was developed for rescuing the LM from an elliptical orbit, it can equally well be applied to rescuing the LM from a circular orbit. However, in that case the expedient of a direct, Hohmann transfer from the CSM orbit

to the LM, with phasing adjusted by delay of the first burn, provides a simpler alternative.

S. L. Levie, Jr.

2011-SLL-vh

Attachments
Reference
Figures 1-5

REFERENCES

1. Anselmo, D. R., and Toms, D. J., "Feasibility of a Simplified LM Ascent and Rendezvous Scheme," Bellcomm Memorandum for File, March 20, 1968.

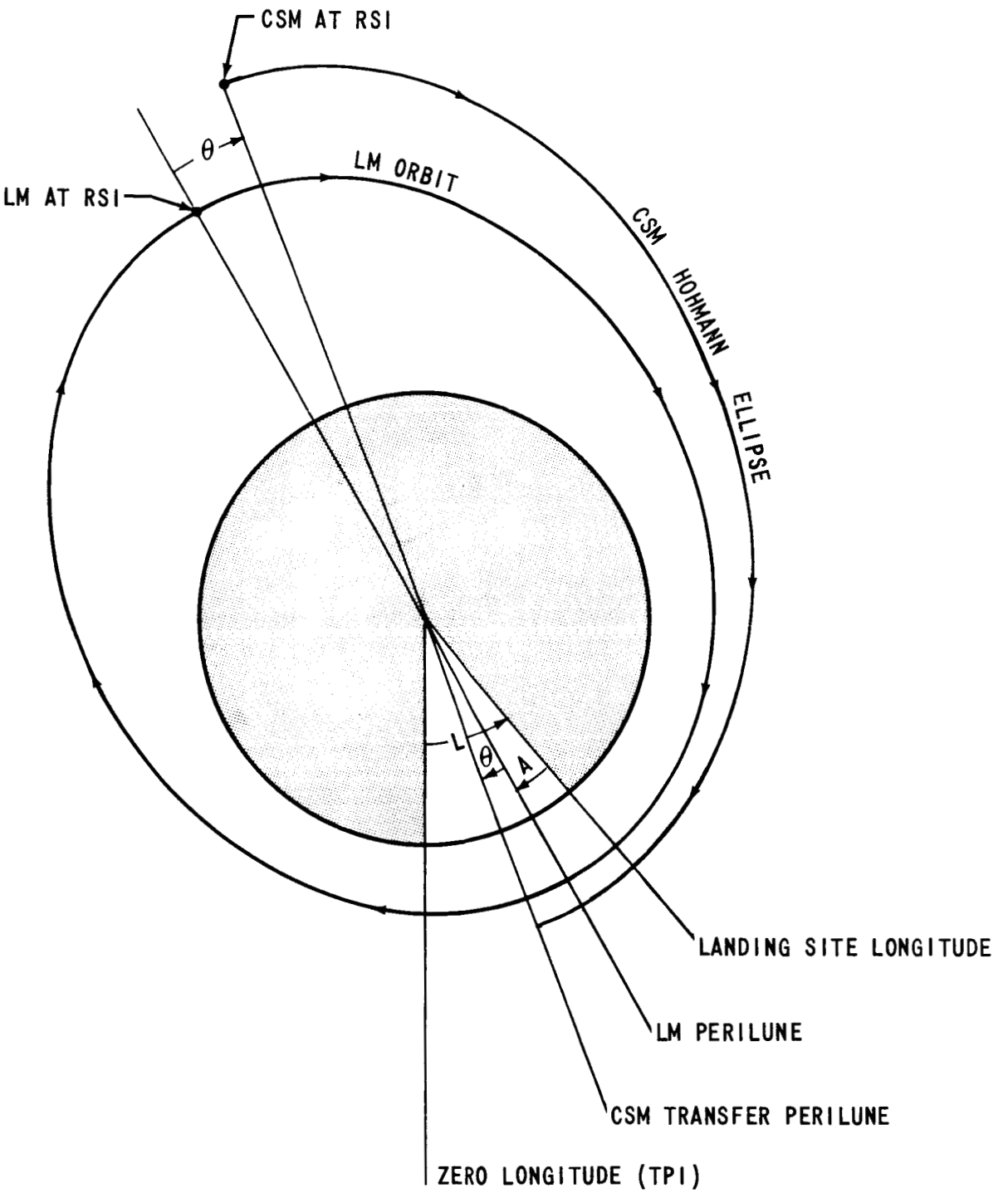

FIGURE I - PART OF THE LM RESCUE GEOMETRY. (VIEW LOOKING DOWN ON MOON'S NORTH POLE)

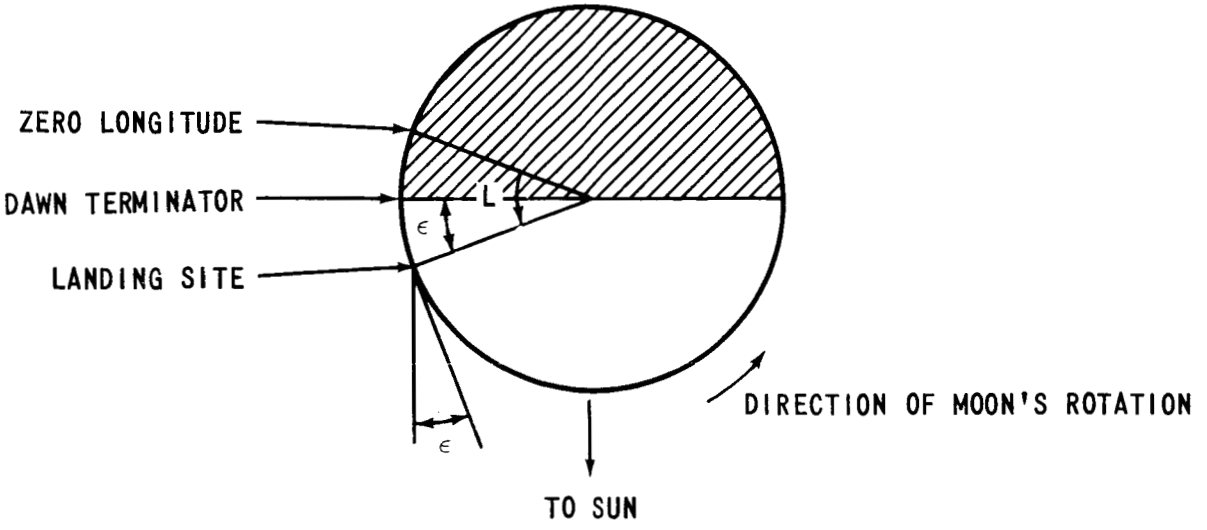

FIGURE 2 - RELATION BETWEEN THE LIGHTING CONSTRAINT AND THE LANDING SITE LOCATION ($\epsilon \sim 10°$)

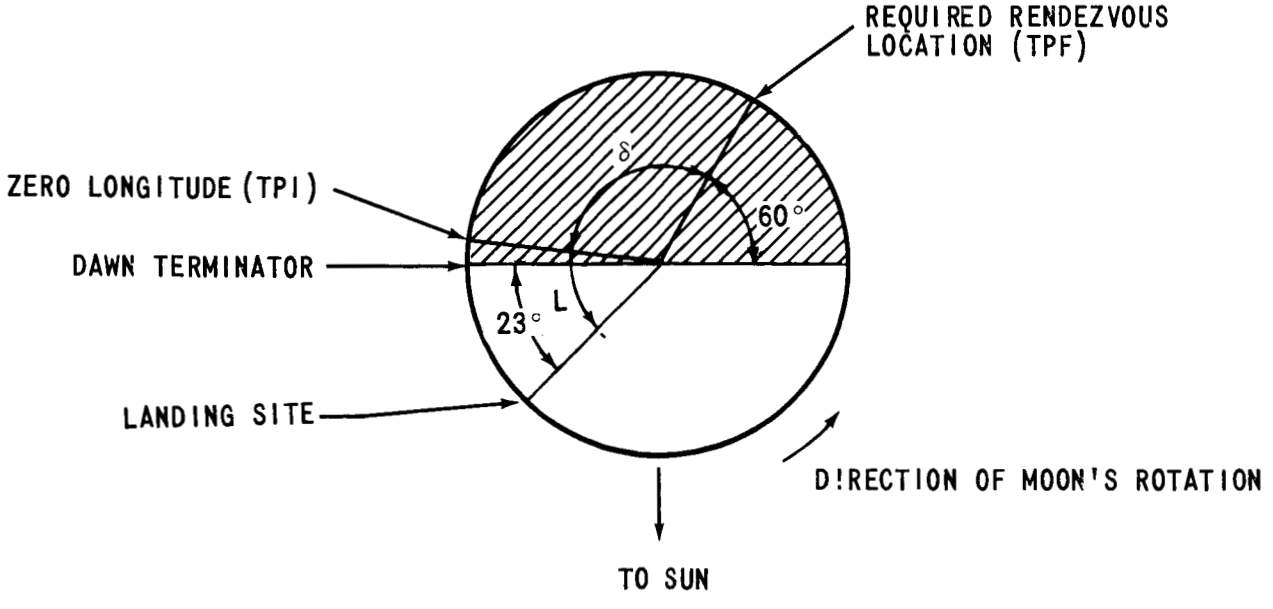

FIGURE 3 - RESCUE GEOMETRY AT LM LAUNCH. NOTICE THE (APPROXIMATE) LOCATIONS OF TPI AND TPF

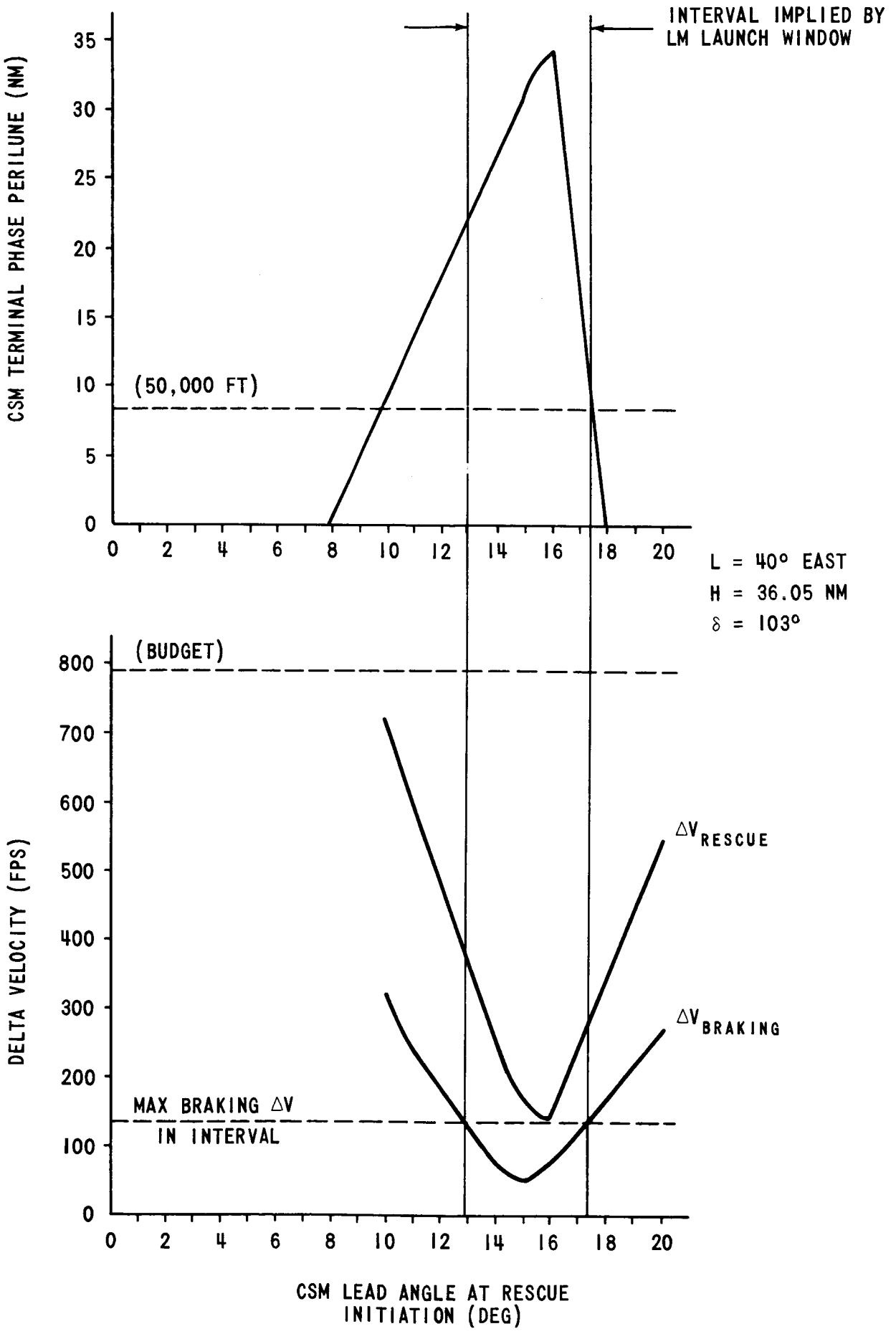
INTERVAL IMPLIED BY
LM LAUNCH WINDOW
CSM TERMINAL PHASE PERILUNE (NM)
35
30
25
20
15
10
5
0
(50,000 FT)
0 2 4 6 8 10 12 14 16 18 20
L = 40° EAST
H = 36.05 NM
δ = 103°
(BUDGET)
800
700
600
500
400
300
200
100
0
DELTA VELOCITY (FPS)
ΔV RESCUE
ΔV BRAKING
MAX BRAKING ΔV
IN INTERVAL
0 2 4 6 8 10 12 14 16 18 20
CSM LEAD ANGLE AT RESCUE
INITIATION (DEG)

FIGURE 4

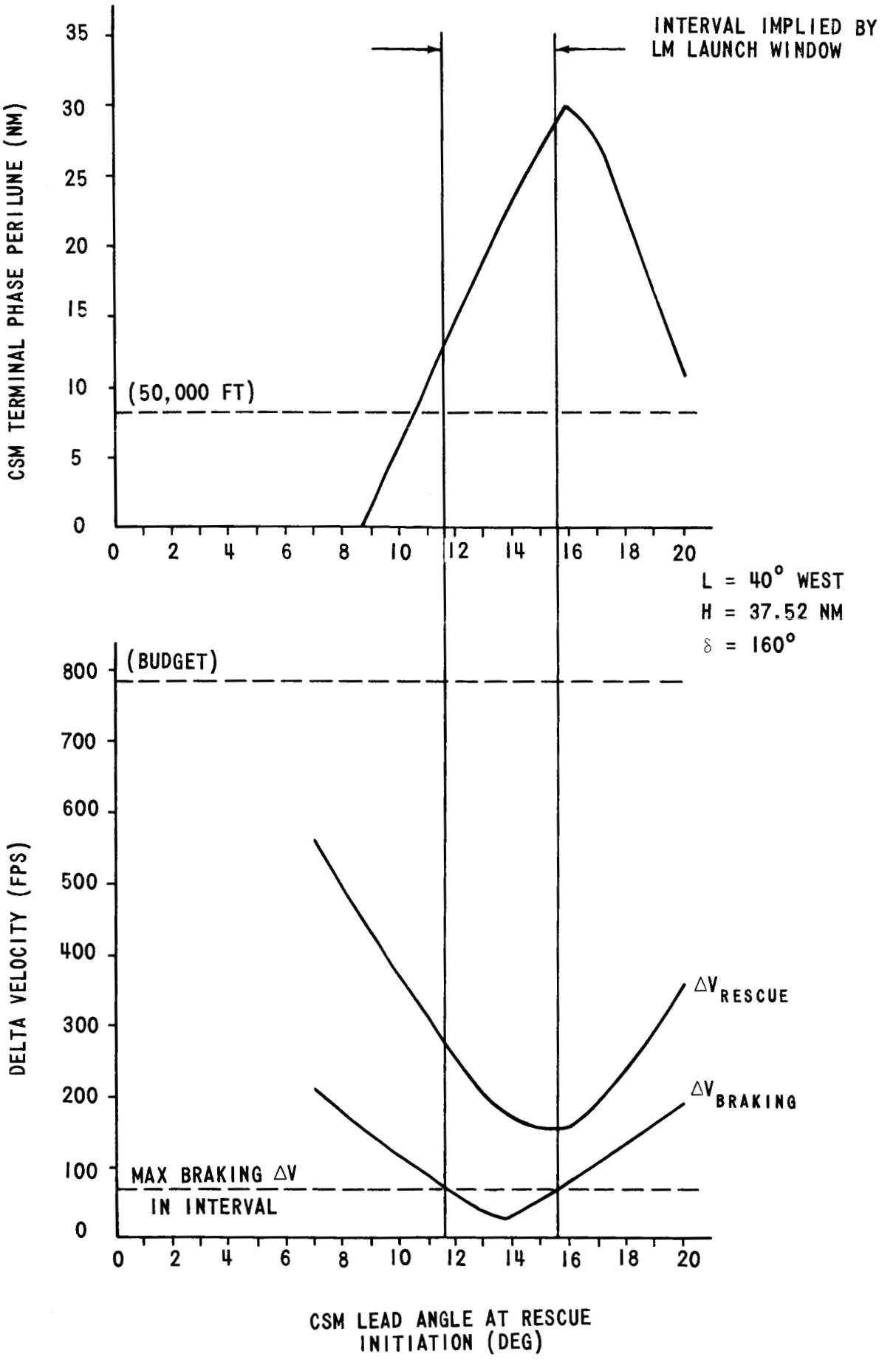
INTERVAL IMPLIED BY
LM LAUNCH WINDOW
CSM TERMINAL PHASE PERILUNE (NM)
35
30
25
20
15
10
5
0
(50,000 FT)
0 2 4 6 8 10 12 14 16 18 20
L = 40° WEST
H = 37.52 NM
δ = 160°
(BUDGET)
800
700
600
500
400
300
200
100
0
DELTA VELOCITY (FPS)
ΔV RESCUE
ΔV BRAKING
MAX BRAKING ΔV
IN INTERVAL
0 2 4 6 8 10 12 14 16 18 20
CSM LEAD ANGLE AT RESCUE
INITIATION (DEG)

FIGURE 5